r Program Plan

Design of Heavy Vehicles

ly written by

ore National Laboratory

Sandia National Laboratories

University of Southern California

California Institute of Technology

NASA Ames Research Center

Summary

The goal of the proposed activities is to develop and demonstrate the ability to simulate and analyze aerodynamic flow around heavy truck vehicles using existing and advanced computational fluid dynamics (CFD) tools. The final products are validated CFD tools that can be used to reduce aerodynamic drag of heavy truck vehicles and thus improve their fuel efficiency.

The project is divided into two related and overlapping efforts:

   Advanced Computations and Experiments of Benchmark Geometries

   Evaluation of Current and New Technologies

Each effort has near-term deliverables as well as longer-term goals. The computations and experiments will provide rapid results for simple benchmark geometries, and will advance to more complex geometries. The evaluation of current and new technologies will provide continued assessment for promising emerging technology.

A Multi-Year Program Plan

for the Aerodynamic Design of Heavy Vehicles

Jointly written by

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The project tasks and deliverables are as follows

Computations and Experiments

1) Simulation and analysis of a range of generic shapes, simplified to more complex, representative of tractor and integrated tractor-trailer flow characteristics using computational tools,

2) The establishment of an experimental data base for tractor-trailer models for code/computational method development and validation. The first shapes to be considered will be directed towards the investigation of tractor-trailer gaps and mismatch of tractor-trailer heights.

3) The evaluation and documentation of effective computational approaches for application to heavy vehicle aerodynamics based on the benchmark results with existing and advanced computational tools compared to experimental data, and

4) Computational tools and experimental methods for use by industry, National Laboratories, and universities for the aerodynamic modeling of heavy truck vehicles.

Evaluation of current and new technologies

1) The evaluation and documentation of current and new technologies for drag reduction based on published literature and continued communication with the heavy vehicle industry (e.g., identification and prioritization of tractor-trailer drag-sources, blowing and/or suction devices, body shaping, new experimental methods or facilities), and the identification and analysis of tractor and integrated tractor-trailer aerodynamic problem areas and possible solution strategies.

2) Continued industrial site visits.

It should be noted that 'CFD tools' are not only the actual computer codes, but descriptions of appropriate numerical solution methods. Part of the project effort will be to determine the restrictions or avenues for technology transfer.

It is recognized that *advanced* computational tools are needed to simulate and analyze tractors and fully-integrated tractor-trailers and to provide accurate modeling of add-on devices. The development and experimental validation of those advanced computational tools is a 'longer-term' effort with a research and development component. Much of the research and development is being paid for via the Department of Energy/Defense Program (DOE/DP) Accelerated Strategic Computing Initiative (ASCI) funding which will be putting serial software packages on parallel machines.

The issues related to the integration and use of aerodynamic add-on devices and a fully-integrated tractor-trailer should be addressed with industry throughout this effort. Acceptance by industry and careful planning of the simulations, analysis, and testing efforts are critical to the success of the entire project. Communications through documentation and meetings with an Advisory Committee of industrial representatives will be part of the Project as well as continued industrial site visits.

Figure 1 provides a chart showing the project flow. The involvement of the Trucking

Industry in collaboration with DOE, Universities, and Laboratories is indicated on the chart by their participation throughout the project. The chart also shows that all computations will be experimentally validated to determine the accuracy of the computational methods and approaches for heavy vehicle simulations.
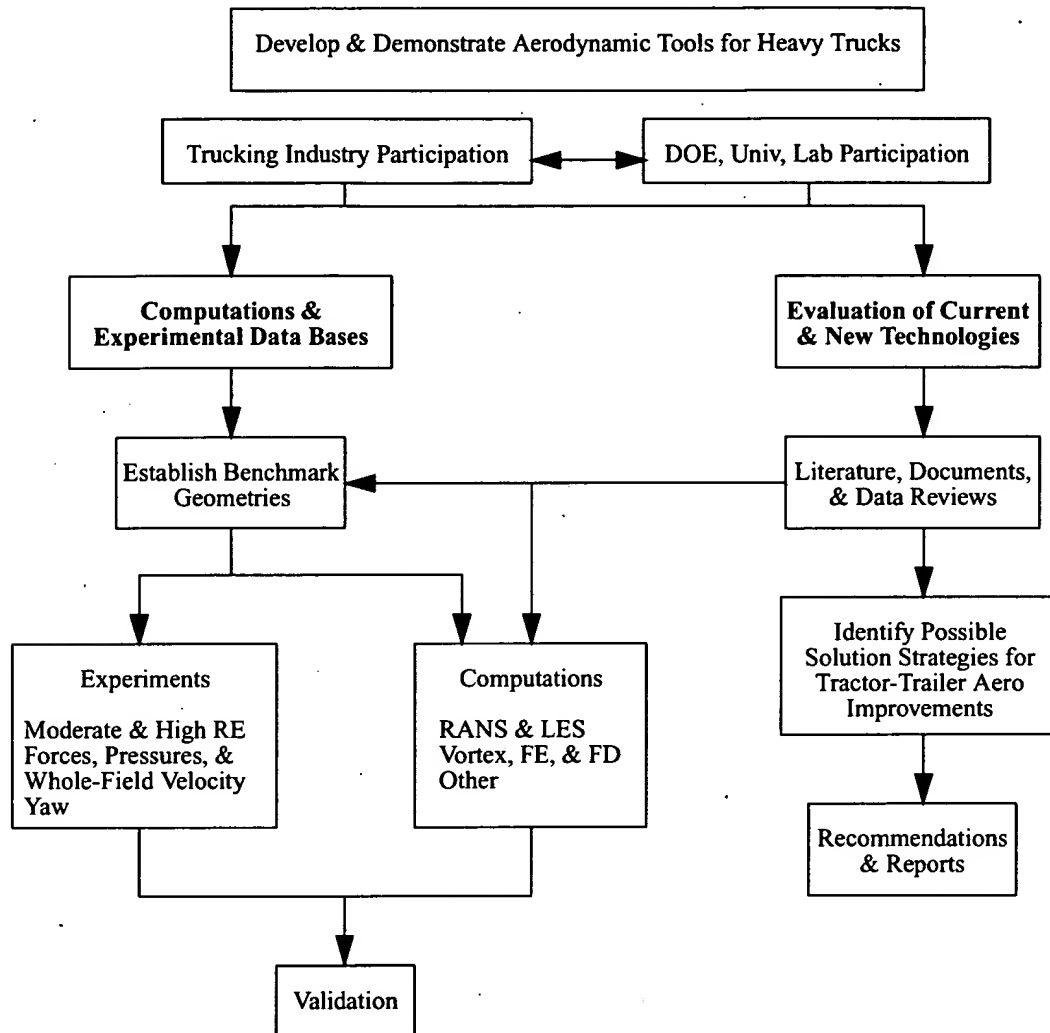

FIGURE 1. Project flow chart.

Background

The achievement of reduced fuel consumption hinges upon the availability of trucks having greater aerodynamic efficiency. In the past twenty years, drag coefficients for typical large trucks have decreased by about 30% - from the range C_D = 0.8-1.0 to C_D = 0.5-0.7. Note that the drag coefficient, C_D, is a dimensionless drag force defined as the drag force/ (dynamic pressure x projected area). The tractor aero-shields were the first major drag improvements, and newer truck cabs possess a more aerodynamic shape and an integrated trailer-shield. Economical travel will require even greater efforts to integrate tractor and trailer design in one clean aerodynamic-package.

Figure 2 contains the estimated horsepower associated with aerodynamic drag in comparison to the power required to overcome rolling resistance and to supply needed auxiliary power, plotted as a function of speed.The truck in question is a modern Class 8 tractor-trailer possessing a wind-averaged drag coefficient of C_D=0.60, and weighing 80,000 pounds. At a speed of about 50 miles per hour, the horsepower contribution required to overcome aerodynamic drag, and the contribution required to overcome rolling resistance/ auxiliary power are about equal. For higher speeds the aerodynamic contribution becomes progressively more dominant. At 70 miles per hour, overcoming aerodynamic drag represents about 65% of the total energy expenditure for a typical heavy truck vehicle. Truck cruising speeds in the range of 70-80 miles per hour are not uncommon.
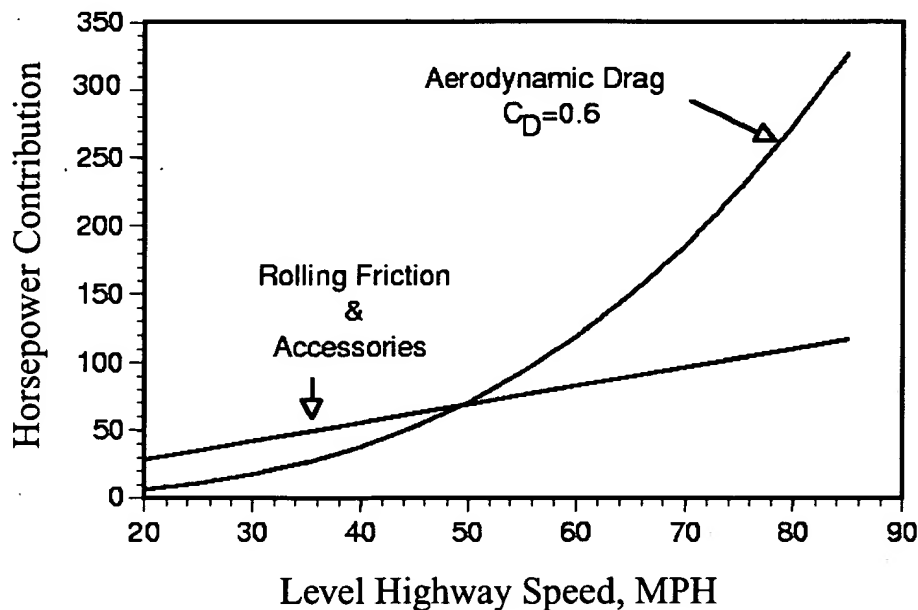

FIGURE 2. Horsepower required to overcome aerodynamic drag and rolling friction/accessories as a function of travel speed for a typical Class 8 tractor-trailer.

It is conceivable that present day truck drag-coefficients can be reduced from C_D = 0.5-0.7 to maybe as low as C_D = 0.3, which represents an ambitious goal of approximately 50%.

There are several reasons for our confidence in these projected improvements. First, automobiles have undergone comparable improvements, and the cars of today are still not optimum aerodynamic shapes, due to styling considerations. Truck design is more strongly driven by economic considerations. If a near-optimum aerodynamic design that meets payload and functionality requirements and contributes to fuel savings for the operator should become available, it would likely be adopted.

Figure 3 illustrates the overall economic benefit associated with reductions in aerodynamic drag as a function of vehicle speed. The ordinate on the left presents calculations of fuel consumption in gallons per mile traveled for a typical Class 8 tractor-trailer powered by a modern, turbocharged diesel engine operating at a fixed specific fuel consumption, bsfc=0.34 #/HP-hr. Five estimates of fuel consumption are shown, corresponding to five values of wind-averaged drag coefficient between C_D=0.7 and 0.3. To the right are plotted the total yearly fuel expenditures expressed in billions of gallons based upon the estimate of 60 billion highway miles traveled (per year) in the year 2012 by Class 8 trucks. The 60 billion highway miles is predicted by applying a 30% growth factor to the FHWA annual vehicle-travel estimates for 1992 (Highway Statistics 1992, p 207, US Government Printing Office, SSOP, Washington DC 20402-9328). Reducing the drag coefficient from 0.6 to 0.3 for a typical Class 8 tractor-trailer would result in a total yearly savings of 3 billion gallons of diesel fuel for travel at a present day speed of 60 miles per hour. The mileage improvement is from 6.1 miles per gallon to 8.7 miles per gallon - a 43% savings.
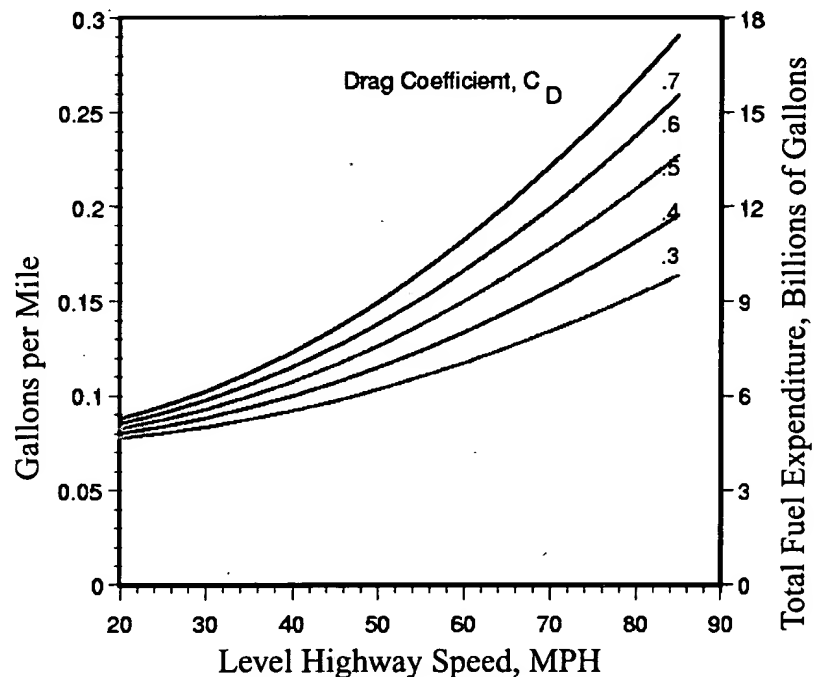
FIGURE 3. Fuel expenditures for a typical Class 8 tractor-trailer as a function of travel speed and drag coefficient.

It should be noted that aerodynamic issues extend beyond the desire for improved fuel economy. They include the assurance of sufficient vehicle stability for safe handling at

highway speeds, as well as the minimization of harmful interactions with other vehicles on the roadway. These interactions occur as aerodynamic loads on nearby vehicles, and by means of unwanted splash and spray raised from the roadbed. The attainment of a satisfactory aerodynamic design must include the mitigation of potential buffeting and turbulence loading on nearby vehicles.

Finally, it is important to consider constraints imposed by federal laws, city driving, and functionality. In particular, add-on devices must meet design constraints imposed by the US Department of Transportation. Although aerodynamic add-on devices have resulted in fuel savings for the trucking industry, it has sometimes impacted maintenance and operational costs. A study conducted by the Maintenance Council of the American Trucking Association found that *tractor* mounted aerodynamic devices can cause components to operate at higher temperatures, can cause unwanted debris buildup and corrosion due to retained moisture, can result in reduced visibility, damage at loading docks, poor mounting hardware, increased wind buffeting, reduced access to maintenance items, and increased tractor-trailer weight and brake loads. Similar concerns and additional operational issues can also exist for *trailer* add-on devices. In addition, add-on devices must be effective in both up-front costs as well as their life-cycle cost.

Aerodynamic Simulation Utilizing Computational and Experimental Simulation

Flow-Field Modeling: Aircraft versus Heavy Trucks

At present, the aerodynamic design of heavy trucks is based largely upon wind tunnel estimation of forces and moments, and upon qualitative streamline visualization of flow fields. No better methods have been available traditionally, and the designer/aerodynamicists are to be commended for achieving significant design improvements over the past several decades on the basis of limited quantitative information.

The trucking industry has not yet tapped into advanced design approaches using state-of-the-art computational simulations to predict optimum aerodynamic vehicles. Computational analysis tools can reduce the number of prototype tests, cut manufacturing costs, and reduce overall time to market.

Throughout this time, numerical codes have been extensively used in the aircraft industry to aid the design process. Why are they not more utilized for ground vehicles? The reason, we believe, lies with the geometry of the two vehicles (aircraft versus truck) and with the nature of the simplifying approximations which can be justified. Aircraft are more slender than trucks, and flow fields about slender bodies are less complicated. An aircraft's flow-field has traditionally been divided into an outer, inviscid flow and an inner, boundary-layer flow. The inner, boundary-layer flow is the difficult one to calculate, but the process is simplified by the fact that the boundary layer remains thin and attached for an aircraft. Outer flow calculations then provide information needed to make the boundary-layer calculation. Modern computational techniques do not make this separation explicitly, but their success in modeling aircraft flow-fields is nonetheless related to the slenderness

issue.

By contrast, a comparable understanding of the flow field about a large truck (a much more bluff object) is one of the grand challenges in the field of aerodynamics. The flow is strongly three-dimensional and turbulent, and it contains significant regions of separated flow that are unsteady in time. Most computational schemes presently in use are not well suited to handle such flows, and hence do not provide convincing information for the designer. However, as computer speed and memory capacity improve and as numerical algorithms and the modeling of turbulence effects improves, the ability to achieve practical, accurate calculations for trucks becomes possible. We believe now is the time to start such a computational effort. The next several paragraphs briefly outline a strategy for both computation and experimental verification and the enclosed work plan will present more specific plans and goals.

Present and Future Computational Possibilities for Heavy Trucks

In any discussion of computational aerodynamics, it is necessary to distinguish between computer algorithms (or codes) which are sufficiently documented and understood so as to be available as a design tool, and those procedures or codes which are presently near the forefront of computing research. Into the first category are placed many of the commercially available codes which usually predict a *steady* time-averaged flow field. In addition, these existing design tools utilize models which have empirically based parameters which are often determined by experiment before parametric design studies can be performed. With the proper experimental validation process, these tools can provide guidance for some general shapes and the complete truck system with some resolution of under-body flow, wheels, mirrors, and gaps between the tractor and trailer. However, these Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) tools may not capture details which are inherently time dependent. In some cases, these unsteady effects are important in refining the truck aerodynamic design and should be included. However, CFD tools more sophisticated than RANS are not developed to the point to be useful for large-scale complex flow-fields and continued research is still needed to advance these tools.

For a comprehensive calculation of the entire flow-field, a more fundamental approach needs to be considered. One such approach is the large-eddy simulation (LES) technique now under study at many universities and government laboratories. The numerical implementation of LES can be accomplished by finite element methods (FEM), finite difference methods, or Lagrangian approaches termed vortex methods wherein small vorticity elements (or vortices) are directly followed throughout the flow field. The latter procedure is efficient in that only fluid parcels carrying vorticity need be followed, and no computational grid is necessary. All implementations resolve the time dependence of all important large scales of the full three-dimensional flow. The only modeling required in LES is that necessary to account for the effects of the small scales of turbulence, i.e., those scales not explicitly computed by LES. This is termed subgrid-scale modeling. In addition, LES is computationally intensive. Present day computers are not large enough nor fast enough to utilize LES to calculate the flow field around an entire truck. However, time is on the side of these fundamental procedures. As computers inevitably improve in performance, it

becomes realistic to think of incorporating these computational tools into a design procedure. An integrated tractor-trailer design that achieves a drag reduction of 50% will require a long-term commitment to computational aerodynamics development. We believe now is the time to begin such a development.

To validate the three-dimensional time-dependent predictions by LES, experimental measurement of the unsteady flow is needed. Commonly, experimental methods only provide steady time-averaged data. There is a significant new computer-based experimental technique which can provide enhanced quantitative flow-field estimation. This is the digital particle image velocimetry (DPIV), or a recent variant termed correlation image velocimetry (CIV). Either one is capable of providing thousands of instantaneous flow vectors in a single flow plane. Such detailed observation of actual flow-fields is also needed for design purposes and for validation of computational solutions. CIV is currently in a development stage, but is progressing in rapid strides. It will be the measurement tool of the coming century, and will be of immense value when it can be utilized routinely by industry.

Most aerodynamic experiments take place in wind tunnels having a fixed ground plane. In the frame of the truck however, the ground is moving so the wind tunnel simulation is imperfect. For complete simulation, the boundary layer on the ground plane must be made insignificant. Removal of the unwanted ground plane boundary layer is often accomplished by means of a boundary layer scoop, or by means of distributed suction. A wind tunnel having a moving ground plane is presently being designed at University of Southern California (USC). It will be available in several year's time, and will be particularly useful in studying the details of underbody flows including the flow about wheels and within wheel-wells. Note that when wheels are rolling on the ground plane, it is not possible to simultaneously study the effect of a side wind.

Recently a novel 'wind tunnel' was suggested by Foss (Automotive Aerodynamic Force Evaluation Facility (AAFEF), patent application, John Foss, Michigan State University, September 1997). In it, the truck is mounted upon a carriage resting on a track below the surface. Relative motion is produced not by conventional fans as in a wind tunnel, but by towing the truck along the track. To make force measurements, the truck mount must employ a fluid bearing to insure smooth movement. Such an idea might form the basis of a National Measurement Facility to be used by industry.

In summary, existing computational tools with experimental validation can be used in the near term to begin investigating truck design improvements for individual flow areas. While the entire tractor-trailer can be modeled using the RANS CFD approach, it may be possible to model parts of the truck using both RANS and LES approaches. Such areas of study can focus on rear and frontal flows, under-body flows, tractor-trailer and trailer-trailer gaps, under-hood flows, wheel, wheel-well flows, and spray characteristics.

DOE Involvement and Interaction with Industry

To determine how the DOE can assist the heavy vehicle industry, the DOE and Lawrence Livermore National Laboratory (LLNL) co-sponsored a Workshop on Heavy Vehicle Aerodynamic Drag in Phoenix, Arizona on January 30-31, 1997. The Workshop succeeded in providing a forum for communication between competitors in the heavy vehicle industry, DOE National Laboratories, other government laboratories, and universities. It was the general consensus at the Workshop that the *trailer* design should be the focus of near term efforts, since significant improvements have already been made to *tractor* designs. Improvements to the trailer would have to include changes to a number of areas including the base region, undercarriage, and tractor-trailer gap. However, even the improvements to the trailer cannot, by themselves, produce the entire 50% drag reduction goal; but it is a starting point. With the limited projected improvements using add-on devices, most of the Workshop participants also agreed that an *integrated* tractor-trailer design is needed to achieve significant drag reductions.

At the Workshop, Eugene Olson of Navistar International Transportation Corporation provided a summary of heavy truck development in the US from the 1930's to present day. An interesting conclusion was that truck design is driven primarily by operator economic issues. Also, since the 1950's, engine power has continually increased, allowing larger and boxier trailers to operate. Both circumstances ultimately result from a plentiful supply of inexpensive diesel fuel. The oil embargo of 1973 generated renewed interest in more efficient aerodynamic designs and improvements were made using various add-on aerodynamic devices (e.g., aero-shields, trailer skirts and boattails).

Following the Workshop, a DOE Technical Committee was formed by Sidney Diamond of DOE's Office of Transportation Technology (OTT), Office of Heavy Vehicle Technology (OHVT) to interact with industry and develop a multi-year program plan (MYPP). The Technical Committee first wrote a draft of the MYPP and distributed it to DOE representatives and members of the heavy vehicle industry. To determine and incorporate into MYPP the current and new technologies and industrial practices and needs, the Technical Committee has met and discussed heavy vehicle aerodynamic issues with individuals from universities performing related research and development, small companies developing new technologies, and representatives from major heavy vehicle industries. The Technical Committee also visited the following industrial sites over a three day period from December 9th through the 11th, 1997:

Tractor Manufacturers:

Navistar International Transportation Corporation, Fort Wayne, IN (contact: Gene Olson and Greg Steen)

Freightliner Corporation, Portland, OR (contact: Bill Gouse)

Trailer Manufacturer:

Wabash National, Lafayette, IN (contact: Frank Smidler)

The purpose of the visits was to

Continue information exchange with industry that began with our January 1997 DOE workshop in Phoenix, Arizona, and

Obtain input and comments on the draft MYPP.

A report documenting the results and conclusions from the site visits was completed (Heavy Vehicle Industry Site Visits: Comments from Companies and Conclusions from Technical Committee, R. McCallen, D. McBride, W. Rutledge, F. Browand, A. Leonard, and J. Ross, LLNL Document UCRL 129679, February, 1998). The following is a brief summary of the detailed discussions in the report.

The general comments from the **companies** visited were:

Design of Aerodynamic Vehicles and Interactions between Tractor-Trailer Manufacturers

Industry wide, there is little interaction between tractor and trailer manufacturers with respect to aerodynamic design. The tractor manufacturers believe they know what is needed for design changes and would rather do the design work themselves, however, they would welcome our thoughts/experiments on trailer aerodynamics. The trailer manufacturer, on the other hand, admitted that they do not have the resources to do any proactive drag reduction research or development. They would welcome any help which the DOE may be willing to provide in the area of drag reduction, but only if adequate support (in terms of computational, experimental or field demonstration evidence) were included to enable them to convince their customers of the financial gain to be realized.

Computational Needs

The tractor and trailer manufacturers pointed out many flow areas of concern, where the effects of design changes on drag are not well understood. It would be beneficial to have a computational tool that can provide such design guidance. It was also proposed that the MYPP include the definition of problems involving the flow around generic shapes that exhibit the flow characteristics of heavy vehicles.

In general, industry has not been successful in implementing computational fluid dynamics (CFD) tools for external aerodynamics. The tractor companies also need assistance reviewing the methods used in existing commercial tools. They believe that something more advanced and innovative is needed.

Experimental Methods

The tractor companies are interested in advanced experimental methods for use in their large-scale experiments.

Demonstration of Trailer Add-Ons

If any demonstration is attempted of a trailer add-on aerodynamic device, it should incorporate features to mitigate unintended consequences caused by its implementation, such as failing to accommodate differing state regulations, maintenance, convenience, and interference with loading, unloading, city driving, or visibility. The demonstration should be directed towards proving the trailer add-on's usability as well as its effectiveness.

The general conclusions from the **Technical Team** based on industries' comments:

Near-term and longer-term assistance is needed.

> The Project should address the issues with current, unique capabilities directed toward the area most in need of help - trailer and integrated tractor-trailer aerodynamics, while a longer range effort should be directed toward developing new capabilities needed to more accurately model the flow regimes we know to be important in heavy vehicle aerodynamics.

Computational methods validated by experiment are needed.

> The goal to develop new tools and/or modeling methods, is an important goal in this project. While it is necessary to have industry 'buy-in', we don't feel that industry has the expertise to correctly identify the proper path in this development. The technical· committee has significant expertise and years of experience in fluid dynamics modeling and, through continued consultation with other experts at the National Labs and academia, should be able to evaluate possible 'value returned' from different development paths (i.e., gridless methods vs. structured grids vs. unstructured grids or finite element vs. finite difference vs. vortex approaches or even direct numerical simulation (DNS) vs. large-eddy·simulation (LES) vs. Reynolds-averaged Navier-Stokes (RANS) modeling of turbulent flows).

> Since tractor manufacturers have found existing commercial codes to be largely inadequate to simulate the flow fields of interest, investigation of the regimes of validity of these commercial codes along with a knowledgeable assessment of the validity of other existing, but still developmental, codes would be very valuable in the near term.

> A set of 'generic problems' or 'benchmark geometries' should be defined, the complexity of which would increase as the computational codes become more capable. The cases should be complex enough to capture important bluff-body fluid dynamics, yet simple enough to allow computations to proceed at some realistically high·Reynolds number (i.e., high enough to trigger the flow elements being modeled, yet low enough to allow computations to be made within reasonable machine times). These generic problems should be modeled with the computational tools and validated with experimental results. The quality and completeness of this experimental database becomes of utmost importance for the following reasons. Detailed, high fidelity code validation efforts will ultimately require detailed, time-dependent velocity field data as well as accurate pressure boundary data to support their development. No matter which computational model is used, data at full-scale Reynolds numbers is required to establish the proper transition criteria and turbulence models to be used in the various flow field regimes found on full-scale trucks. The database could also be used by the commercial software companies to evaluate the use of their software.

Demonstration of a device integration process for a trailer add-on would be beneficial.

> Even though industry has not been very successful with trailer add-on devices, it may be possible that with a much closer interaction with both the trailer manufacturers and the fleet operators, this and other trailer aerodynamic problem areas could be addressed and satisfactory solutions found and demonstrated. Any demonstration

effort should address ALL of the impacts (i.e., not just drag reduction) resulting from any trailer modifications.

Continued review and evaluation of current and new technologies is needed.

Due to the lack of aerodynamicists in the trailer manufacturer community, their desire for assistance, the large percentage of the drag that comes from the trailer, the aerodynamics expertise and tools (both computational and experimental) that exist within the DOE, NASA, and the academic community, coupled with the DOE's desire to fund efforts that will result in trailer drag reduction, it would seem logical that the MYPP should include an effort to help the trailer community attempt to improve trailer aerodynamics, providing substantiation of aerodynamic results so they can "sell" those solutions to their customers (i.e., fleet operators). The MYPP should provide for continued review and evaluations of current and new technologies for improving trailer aerodynamics.

The following MYPP was developed based on the comments from industry and the Technical Teams' conclusions and recommendations outlined above.

Multi-Year Program Plan:

Tasks and Deliverables

The purpose of the DOE Heavy Vehicle Aerodynamics MYPP is to use government resources to bring the aerodynamic expertise available in government organizations and academia to bear in assisting the heavy vehicle industry to reduce aerodynamic drag on trucks. The obvious payback from this investment is the reduction in fuel usage and derivative reduction in the U.S.'s dependence on foreign oil imports.

The project is divided into two related and overlapping efforts:

Advanced Computations and Experiments of Benchmark Geometries

Evaluation of Current and New Technologies

Each effort has near-term deliverables as well as longer-term goals. The computations and experiments effort will provide rapid results for simple benchmark geometries, and will advance to more complex geometries. The evaluation of current and new technologies will provide continued assessment for promising emerging technology.

Technology Transfer

It should be noted that 'computational fluid dynamics (CFD) tools' are not only the actual computer codes, but descriptions of appropriate numerical solution methods. The numerical solution methods developed here will be published in the open literature.

The delivery of actual codes will be restricted by normal Laboratory and University policies and all collaborative requirements will have to be met before delivery of software to project collaborators. Software developed at DOE National Laboratories can be shared with industry through collaborative licensing. If a clear benefit is demonstrated from the contributions of one or two industrial participants (e.g., sharing of experimental data), a Cooperative Research and Development Agreement (CRADA) may be considered. Otherwise, all the development work on this project will be shared with all the industrial participants.

Part of the project effort will be to determine the restrictions or avenues for technology transfer.

Advanced Computations and Experiments of Benchmark Geometries

Accurate computational modeling of a fully-integrated tractor-trailer design requires the use of advanced computational tools on parallel processing computers. Current research is extending 3-D Reynolds-averaged Navier-Stokes (RANS) CFD models to massively parallel architectures. However, for some geometries more physical models may be needed. Another more fundamental computational approach is to use large-eddy simulation (LES) which can provide an accurate prediction of the time-dependent three-dimensional flow

separation and reattachment for complex geometries, like the flow around certain sections of a heavy vehicle truck. Accurate prediction of the separation and reattachment positions will contribute to accurate drag predictions and aid in the successful design of a fuel-efficient aerodynamic vehicle. However, the predictive capability of LES depends on the quality of the subgrid-scale model employed. In addition, due to computing resource limitations, LES has not been used for 3D flow fields involving complex geometries. Thus, with the introduction of large, parallel computers and the development of appropriate subgrid-scale models, LES should be able to solve large, practical problems.

To establish the confidence of industry in computational design methods, computational predictions will need to undergo a rigorous verification and validation process utilizing wind tunnel experimentation and field testing of final designs. Validation of computational simulations for these advanced computational tools will require a range of experimental data: from simple shapes to complex, tractor-trailer geometries; including three-dimensional, time dependent as well as steady time-averaged, full-field velocity measurements using advanced diagnostic tools such as DPIV or CIV.

Computation and experiment will be a multi-lab, multi-university effort with the following resources and participants:

- Participants at Sandia National Laboratories (SNL) will use an existing CFD code that utilizes the RANS modeling approach which will provide a time-averaged steady-flow prediction for general aerodynamic design guidance. Such codes are based on the full Navier-Stokes equations and can model the complete aerodynamics of a full-scale tractor-trailer. However, the codes do not explicitly compute the unsteady random turbulent fluctuations in the boundary layer, but rather average them using various 'Reynolds-Stress' models. The effect of this averaging on the accuracy of the modeling of the large vortex shedding is uncertain. Therefore, incorporation of LES models into these existing RANS codes will occupy the major thrust of the SNL CFD effort over the period of the project. This is meant to supply an evolutionary, rather than revolutionary, approach to the modeling of such large-scale structures inherent in large bluff-body flows. The point-of-contact at SNL is Don McBride.

- Participants at LLNL will use a DOE developed code that utilizes an LES approach which can provide detailed time-dependent flow simulations. This code will be used for accurate prediction of flow separation and in regions of the flow where time dependent flow effects are believed to be important. The point-of-contact at LLNL is Rose McCallen.

- Participants at California Institute of Technology (Caltech) will collaborate with LLNL by providing LES subgrid-scale modeling guidance for LLNL's finite-element numerical approach, in addition to complementing LES work with Caltech's vortex-method numerical approach. The vortex-method approach is quite different from the FEM approach (e.g., vortex methods require a grid only on the body surface) and has provided benchmark quality results for unsteady, two-dimensional separated flows but needs further testing of three-dimensional flows. The point-of-contact at Caltech is Anthony Leonard.

- Participants at the University of Southern California (USC) will develop the data base of experimental results for generic shapes representative of heavy vehicle flow characteristics. They will adapt the new flow-field measurement technique CIV for use with heavy vehicle models, in support of the numerical work at LLNL, SNL, and Caltech. The point-of-contact at USC is Fred Browand.

- Participants at NASA Ames will perform high Reynolds number experiments on shapes representative of an integrated tractor-trailer. The point-of-contact at NASA Ames is Jim Ross.

- The determination of appropriate generic shapes will be a joint effort by all participants with guidance from the industrial representatives.

The key to developing more useful and accurate computational methods is to have the developers immersed in the problem and for them to become 'experts' in truck aerodynamics (not necessarily design). Benchmark experiments which provide the necessary level of detail in the measurements to asses the computational methods would be helpful. Such experiments should include not only component studies but full configurations. It is not necessary to simulate road conditions in the experiments. The interaction of the flow over various parts of a truck are important and require proper care and understanding in performing computational analyses. The testing facility and mounting should be included in the CFD analyses in order to completely validate the computational results.

The issue of Reynolds number (Re) should also be addressed. Current testing is done with sub-scale models, often run at higher than road velocities to increase Re. It is still not clear how high a Re is enough to get the 'right' answer for drag.

Carefully designed experiments in the NASA Ames 12-Foot Pressure Wind Tunnel (12 PWT) will provide an excellent source of high quality validation data at high Reynolds number for trucks. The 12 PWT would give 75% of full-scale Re at highway speeds and 100% of highway Re at slightly higher speeds. Existing CFD models could likely be tested at these conditions and the necessary instrumentation would not be prohibitively expensive. The cost of this effort is included in the estimated cost section below.

To demonstrate and evaluate the computational capabilities of RANS and LES in the first to second year of the project, a focussed effort to investigate the drag effects due to trailer-tractor height mismatch and gaps will be undertaken. Moderate to high Re wind tunnel test data will be needed for code validation.

The deliverable for the advanced computations and experiments effort will be a document that provides a summary of benchmarking results with the computational tools compared with experimental data.

Additional Resources

The parallelization of the aerodynamic flow codes will be funded by the Advanced Strategic Computing Initiative Project (ASCI) at both LLNL and SNL. Use of the most powerful parallel computers world wide, with teraflop capability, will also be provided by the ASCI project for both code development and for the aerodynamic simulation of fully-integrated

truck designs. Caltech is also leveraging ASCI Alliance funding for code parallelization and enhancements, and they have access to their Caltech on-site parallel computers at no charge, as well as access to the ASCI computers.

Through a grant from Department of Defense (DOD) a wind tunnel at USC has been instrumented with DPIV instrumentation. Another wind tunnel at USC is being reassembled with a moving ground plane and instrumented with sophisticated DPIV instrumentation with proposed funding from the National Science Foundation (NSF) and industry. These wind tunnels and equipment will be available for use in this project.

The DOE Office of Transportation Technology (OTT) funding is needed for the manpower time in performing the flow analyses, developing improvements in modeling methods particular to modeling of truck separation-regions, and to provide detailed flow-field wind-tunnel data for code validation.

In summary, SNL and LLNL will be funded by leveraged funds for code parallelization and will have full access to ASCI computer resources. Caltech will also leverage its ASCI Alliance funding and access to ASCI computer resources. Wind-tunnel validation experiments will be performed by USC in their university wind tunnels (or other wind tunnels, if appropriate), where the experimental manpower effort and equipment use will need to be funded by DOE OTT. The purchase of DPIV equipment and tunnel enhancements is being supported by USC's leveraged funds from DOD and NSF.

Evaluation of Current and New Technologies

The first step in this project is to identify the areas of the tractor-trailer flow which have the most significant impact on the (total) drag of a heavy vehicle. A prioritized list of tractor-trailer drag contributions (e.g., from tractor-trailer base flow, tractor-trailer gap flow, underbody flow, wheel, and wheel-well flows) will be developed. The most expedient approach to identifying the component drag contribution is from existing experimental data. Information will be solicited from the open literature, from industry, and from the American Trucking Associations Foundation.

After the important flow areas have been identified, possible design improvements for individual flow areas will be analyzed, without complete, detailed modeling of the entire truck. For example, the effect of rounding corners on the front and rear of the trailers compared to more typical squared corners may be an area of focus.

Technological developments intended for application to heavy vehicles must be monitored constantly. It is also possible that technological development in related areas, such as airplane aerodynamics, might be successfully applied to improve the performance of trucks. Recent examples are: the possible use of boundary layer blowing (Development of pneumatic aerodynamic concepts for control of lift, drag, and moments plus lateral/directional stability of automotive vehicles, Englar, Smith, Niebur & Gregory, SAE Paper No. 960673, 1996), and the use of zero mass flow excitation (Oscillatory blowing, a tool to delay boundary layer separation, Seifert, Bachar, Wygnanski, Koss & Shepshelovich, AIAA Paper No. 93-0440, 1993, Boundary layer control by periodic addition of momen-

tum, Wygnanski, AIAA Paper No. 97-2117, 1997, Modification of the aerodynamic characteristics of bluff bodies using fluidic actuators, Amitay, Honohan, Trautman & Glezer, AIAA Paper No. 97-2004, 1997). All these interesting concepts must be carefully evaluated.

The deliverable for this effort will be a document containing a summary of the present state-of-the-art as obtained from published literature and continued communication with the heavy vehicle industry, and our best assessment of current and new technologies for drag reduction and for improved tractor-trailer performance.

Task Descriptions

Advanced Computations and Experiments of Benchmark Geometries

1.Establish Benchmark Geometries

Through collaboration with industry, generic tractor-trailer benchmark models will be established. There will be a range of shapes, simplified to more complex, representative of tractor-trailer flow characteristics. The responsibility for this effort is USC's and the point-of-contact is Fred Browand. However, all participants will be involved in the decision making.

2.Computations

The analysis will be performed using computational simulations validated with experiments to establish accuracy and the ability of the models to simulate heavy vehicle aerodynamics. SNL, LLNL, and Caltech will perform numerical calculations and analysis of the validated results.

This task will involve code parallelization of the LLNL and SNL incompressible aerodynamic flow codes. Manpower time and use of computer resources will be provided by leveraged funds.

Fluid flow model improvements will be part of this effort: a) Improvement of low-speed RANS turbulence models by SNL, and b) The development of improved LES modeling methods particular to the modeling of truck flow separation regions. Model development will be done at LLNL and SNL in collaboration with Caltech. The point-of-contact at LLNL is Rose McCallen and at Caltech is Tony Leonard.

For the investigation of drag effects due to trailer-tractor height mismatch and gaps, undertaken during the first and second years of the project, RANS computations will be performed by SNL, LES/FEM computations will be performed by LLNL, and LES/Vortex Method will be performed by Caltech.

Some manpower time and all computer resources will be provided by leveraged funds.

3.Experiments

An experimental data base for the tractor-trailer benchmark models for code/computational method development and validation will be generated by wind tunnel testing. USC and NASA Ames will perform the experiments.

In the investigation of trailer-tractor height mismatch and gaps, moderate Re tests will be performed at USC and high Re tests will be performed at NASA Ames. SNL will also provide test data from past studies on the same simple integrated tractor-trailer shape but with no gap or height mismatch and at Reynolds number less than, but approaching, the high Reynolds numbers described above.

The point-of-contact for USC is Fred Browand and for NASA Ames is Jim Ross.

4.Documentation and Publication

Each member of the team will contribute to the documentation of this project with the responsibility of the final published document to be that of the LLNL Project Leader, Rose McCallen. Since the document will originate from a DOE Laboratory, publication costs will include DOE review and release as well as the general copying and distribution of the document.

Evaluation of Current and New Technologies

1. Identification and Prioritization of Tractor-Trailer Drag Sources

This task will include review of the

- Open literature,
- Industry data, and
- Data provided by the Trucking Associations.

The responsibility for this effort is USC's and the point-of-contact is Fred Browand. However, NASA's point-of-contact, Jim Ross, and Tony Leonard, point of contact at Caltech, will work directly with Fred Browand on this effort and all participants will be involved in this effort.

2. Evaluation of Current and New Technologies

Evaluation of technologies for drag reduction based on published literature and continued communication with the heavy vehicle industry (e.g., blowing and/or suction devices, body shaping, new experimental methods or facilities). The responsibility for this effort is USC's and the point-of-contact is Fred Browand. However, all project participants will be involved in this effort.

3. Identification and Analysis of Specific Tractor-Trailer Problem Areas

Specific tractor-trailer aerodynamic problem areas and possible solution strategies will be identified and analyzed, while working closely with our industrial contacts through continued industry site visits. The NASA point-of-contact, Jim Ross, and the SNL point-of-contact, Don McBride, will share the responsibility for this effort, and will closely coordinate their efforts with USC's Fred Browand.

4.Documentation and Publication

Each member of the team will contribute to the documentation of this project. However, the responsibility of the final published document for the drag source identification and the evaluation of technologies will be that of the USC point-of-contact, Fred Browand and the responsibility of the final published document for the identification and analysis of tractor-trailer problem areas will be that of the SNL point-of-contact, Don McBride. Since the

SNL document will originate from a DOE Laboratory, publication costs will include DOE review and release as well as the general copying and distribution of the document.

Deliverables

Advance Computations and Experiment of Benchmark Geometries

1) Established range of shapes, simplified to more complex, representative of tractor-trailer flow characteristics using computational tools,

2) An experimental data base for tractor-trailer models for code/computational method development and validation. The first shapes to be considered will be directed towards the investigation of tractor-trailer gaps and mismatch of tractor-trailer heights.

3) Documentation of effective computational approaches for application to heavy vehicle aerodynamics based on the benchmark results with the computational tools compared to experimental data, and

4) Computational tools and experimental methods for use by industry, National Laboratories, and universities for the aerodynamic modeling of heavy truck vehicles.

Evaluation of Current and New Technologies

1) Documentation of the identification and prioritization of aerodynamic drag sources for heavy vehicles,

2) Documentation of the evaluation of current and new technologies for drag reduction, and

3) Documentation of the identification and analysis of tractor-trailer aerodynamic problem areas and possible solution strategies.

Estimated Project Cost and Milestones

This project is expected to be completed in 5 to 7 years depending on level of support. Table 1 provides estimated total project cost per year and Table 2 outlines the projected milestones for the first four years of the project. Low ranges are shown for FY99 and FY00 for possible adjustments based on available funds.

TABLE 1. Estimated Costs

	Computations & Experiments	Evaluation of Current & New Technologies	Final Report	Total/Year
FY98	$276K	$34K		$310K
FY99	$630K	$5K		$635K
FY99 (low)	($555K)	($5K)		($560K)
FY00	$1,045K	$188K		$1,233K
FY00 (low)	($635K)	($68K)		($703K)
FY01	$1,095K	$188K		$1,283K
FY02	$855K	$161K		$1016K
FY03	$818K	$161K		$979K
FY04	$120K	$124K	$34K	$278K
TOTAL				$5,734K

TABLE 2. Projected Milestones for first four years of project (FY98 through FY01)

Task	Milestone
Workshop II	2/98
MYPP with projected budget and milestones	5/98
Continued site visits	8/98, 12/98, 12/99, 12/00
Level 1 Benchmarks: Establish generic shapes and outline test cases for investigation of trailer-tractor height and gap mismatch (Demo)	9/98
Test data at moderate Re for Level 1 benchmarks (Demo)	9/99
RANS, LES/FEM, LES/Vortex computations of Level 1 benchmarks at moderate Re (DEMO)	12/99
Test data at high Re for Level 1 benchmarks (Demo)	6/00
RANS, LES/FEM, LES/Vortex computations of Level 1 benchmarks at high Re (DEMO)	12/00
Workshop III: Possible computation contest	5/01
Level 2 Benchmarks: Establish generic shapes	9/99
Test data at moderate and high Re for Level 2 benchmarks	9/01